Closed Loop Electrostatic Actuation of Membrane Mirrors

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Mirror Technology Days in Government, June 7–9, 2010

Outline

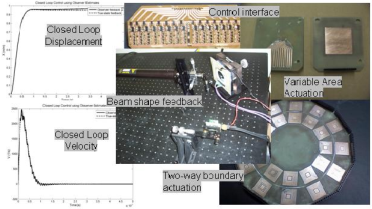
Membrane Mirror Actuation (Not an SBIR/STTR Project)

Innovation

- Development of a dynamically controlled actuation system for membrane mirrors

Accomplishments

- Low-moderate voltage, large deflection,large-force elecrostatic actuation
- Variable-area, variable-gap techniques developed
- Closed loop, current bandwidth $\rightarrow$ 500 Hz.



Government/Science Applications

- Laser and microwave communication
- Nonlinear control with optics feedback

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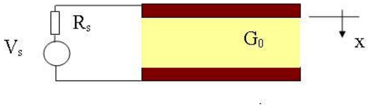
Background

- Large deformable reflectors
  - large actuation authority desirable (i.e, large forces and/or deflections)
- Membrane reflectors (monolithic, conformable, deployable)
  - slow natural response vs. need for greater bandwidths
    - aberration corrections (atmospheric turbulence, slewing dynamics–structural coupling)
    - process requirement (e.g. communication)
- Electrostatic actuation well suited for force and deflection authority requirement

Introduction

- Voltage difference between 2 conductors causes force



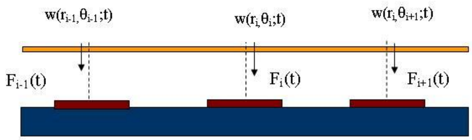
$$F = \frac{\varepsilon V_a^2 A}{2G_0^3(1-X)^2}; \quad \left(X = \frac{x}{G_0}\right) \tag{1}$$

where V_a is the voltage across the electrode, A is the area of the active electrode, and ε is the permittivity, here, of air.

- Active electrode on fixed substrate, metallized membrane provides the neutral electrode

Membrane Actuation

- To produce deflection $w(r, \theta; t)$ at any point, apply force $f(r, \theta; t)$. The force distribution over the membrane could be controlled in real time by controlling
  - voltage on the active electrodes
  - area of the active electrodes
  - gap between the individual active electrodes and membrane



Membrane Actuation (II)

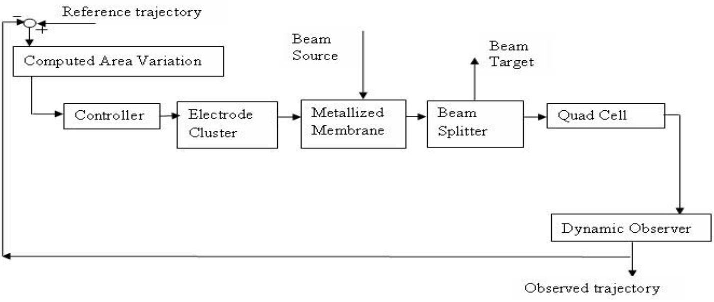
- Voltage control
  - commonly used and intuitive
  - high voltages for large deflections
  - closed-loop control requires accurate manipulation of large voltages
- Area control
  - Segmented active electrodes
  - switching on/off segments to control active area
  - constant voltage
  - closed-loop control now a switching problem
- Gap Control
  - multiple aberration modes using a single control input
  - actuate substrate mechanically; constant voltage, constant area control
  - continuous control

Mirror Actuation for Large Deflection

- Voltage control methods: Zhu et al. (2007), Maithripal et al. (2006), Seeger et al. (2004); closed loop control necessary for deflections $> \frac{1}{3}$ gap size.
- Area control and gap control: results discussed here
- Results published in Korde (2008, 2009, 2010)[1]

[1] *J. Intelligent Material Systems and Structures*, v. 21, January 2010, pp. 61-82
J. Intelligent Material Systems and Structures, v. 20, n. 6, 2009, pp. 697-721
J. Intelligent Material Systems and Structures, v. 19, n. 11, pp. 1339-1359

Single Mode Control



- Deflection range at mirror center → full gap size G_0 (40μm here),
- Tip/tilt deflection → maximum allowed by G_0 (3 mrad here),
- Response bandwidth of 500 Hz.

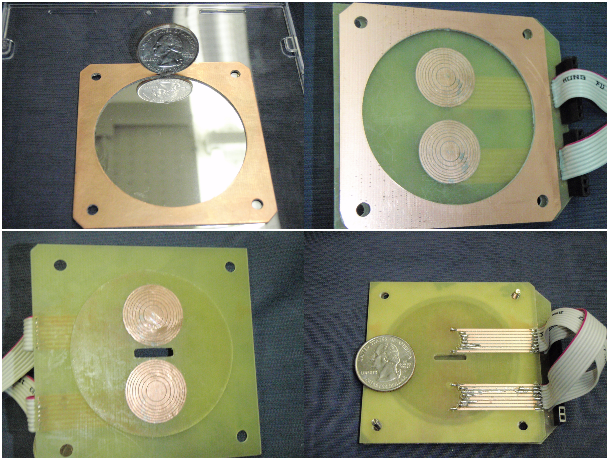
Single Mode Control (II)

- Dynamics (Lumped Parameter Model)

$$\dot{X}_e = V_e$$
$$\dot{V}_e = -KX_e - DV_e + \frac{\varepsilon V_a^2}{2G_0^2(1-X_e)^2 m_e} A(t) \qquad (2)$$

- Nonlinear system
- Mass m_e, stiffness K and damping D from energy considerations

Single Mode Control (III)

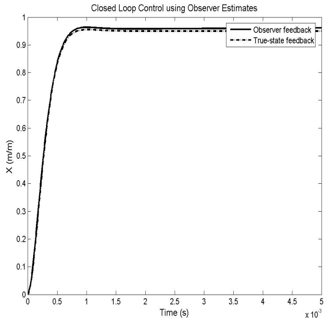


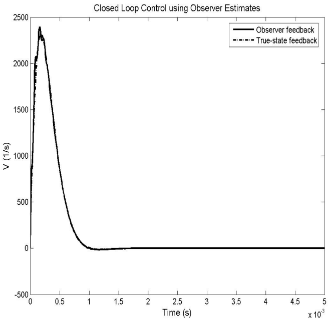
Mirror for single-mode 2-way actuation

Single Mode Control (IV)

- Specify reference trajectory for mirror deflection for focus/defocus or tip/tilt beam deflection
- Compute corresponding reference area variation and discretize to minimum segment area
- Dynamic observer design based on quad cell input
- Lyapunov potential method for variable gain controller design for trajectory tracking

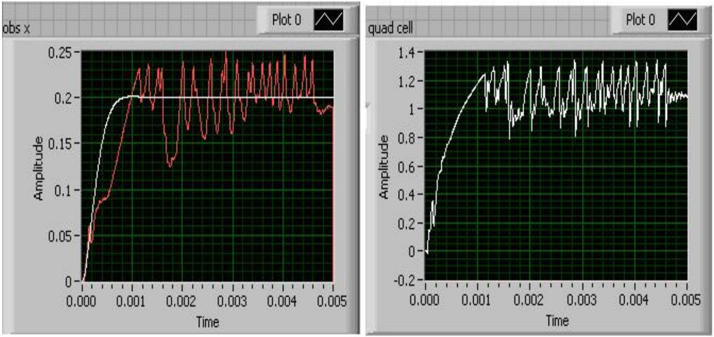
Single Mode Control Results (I)





Simulation results: discrete area control with observer feedback

Single Mode Control Results (II)

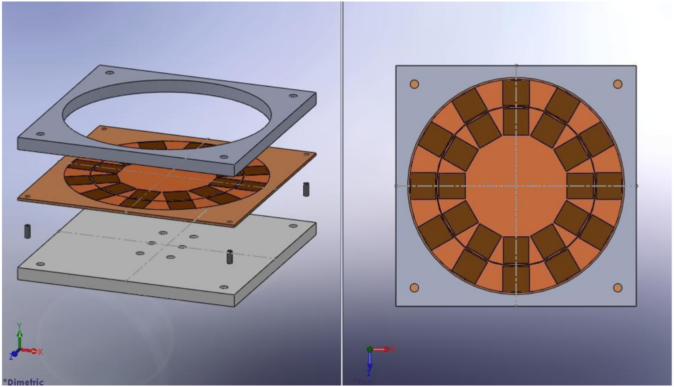


Experimental results: discrete area control with observer driven by quad-cell measurements

Multiple Mode Actuation (I)

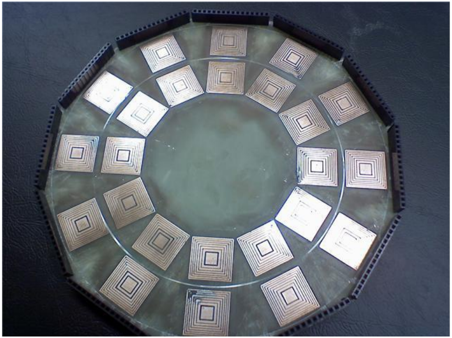
- Up to 12 aberration modes
- Bandwidth of 500 Hz
- Center deflection $\pm 100 \mu$m
- Electrostatic actuators placed along boundary
- Mirror surface metallic
- Closed loop control
- Possible with area control or gap control

Multiple Mode Actuation (II)



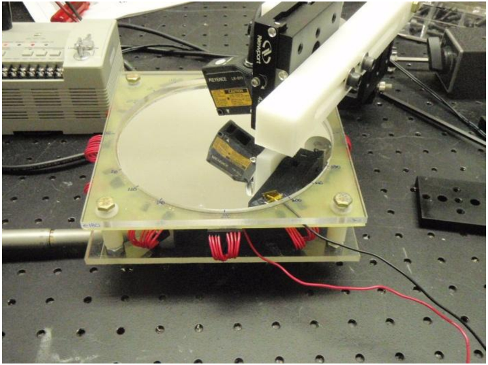
Mirror design

Multiple Mode Actuation (III)



Mirror actuator clusters for variable area control

Multiple Mode Actuation (IV)



Completed mirror undergoing static tests

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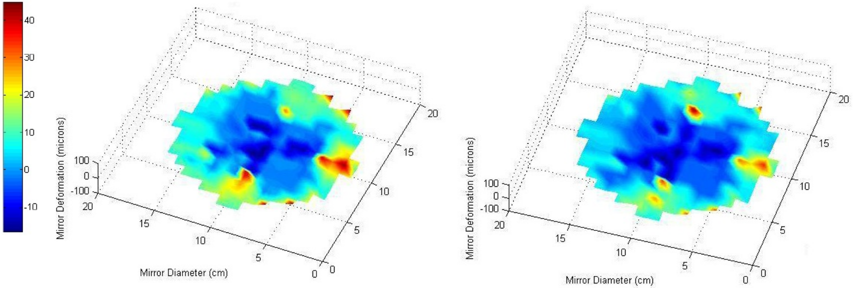
Multiple Mode Actuation (V)

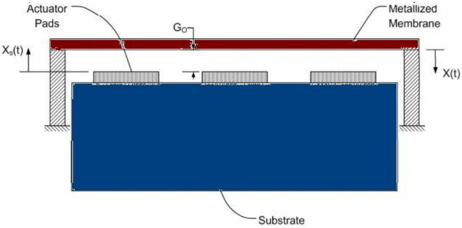


Excitation with 260 V (Left) and 280 V (Right)

Gap Control: Basic Features

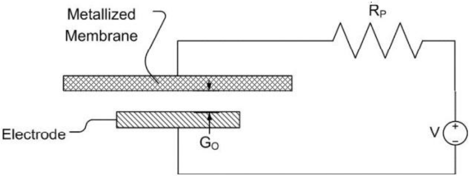
- Mechanical or piezoelectric control of electrode gap
- Single control variable for multiple-mode actuation
- Constant voltage on constant-area electrodes
- Potentially large number of aberration modes
- Switch on/off selected actuators to determine aberration modes corrected for

Gap Control Schematic



Substrate is driven mechanically/piezoelectrically; single control variable $x_s(t)$.

Gap Control Goals



- Bandwidth of 500 Hz.
- Target deflection 60 μm
- Trajectory tracking in the presence of random measurement error and random platform vibration

Dynamic Formulation

Nondimensionalized equations of motion

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= -2\zeta\omega_0 v - \omega_0^2 x + \frac{1}{3}q^2\omega_0^2 + u \\ \dot{q} &= \frac{1}{R_p C_0}\left(-q(1-x) + \frac{2}{3}V\right) \end{aligned} \tag{3}$$

u is the control variable given by

$$-G_0 u \equiv -\ddot{x}_s - \frac{b}{m_e}\dot{x}_s - \frac{k_e}{m_e}x_s \tag{4}$$

where x_s denotes the displacement through which the substrate is driven.

Control Approach

- Reference trajectory for mirror corresponding to deflection and bandwidth
- Corresponding reference trajectory for gap variation
- Closed loop control to keep actual motion on reference trajectory
- Dynamic observer
- Lyapunov potential method
- Controller design to ensure velocity errors $\rightarrow 0$ in the presence of measurement error and platform vibration.
- Measurement error and platform vibration assumed to be 1 st order Markov processes

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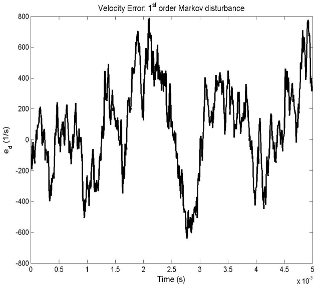
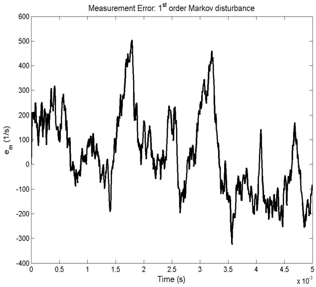
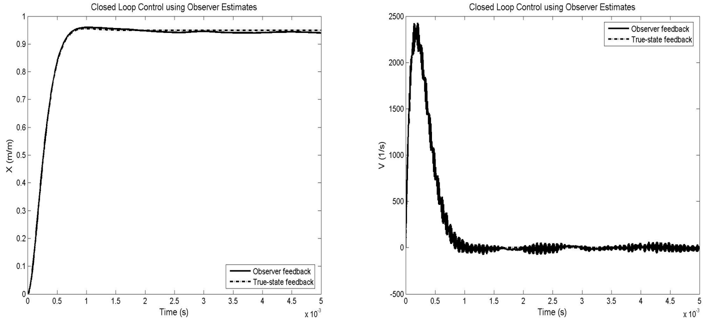
Control against measurement error and platform vibration

- Errors in sensor measurements used in feedback
- Taken to be random but band-limited; 1st order Markov process
- Platform (e.g. air/space vehicle) where mirror is mounted subject to vibration
- Taken to be band-limited; also 1st order Markov process





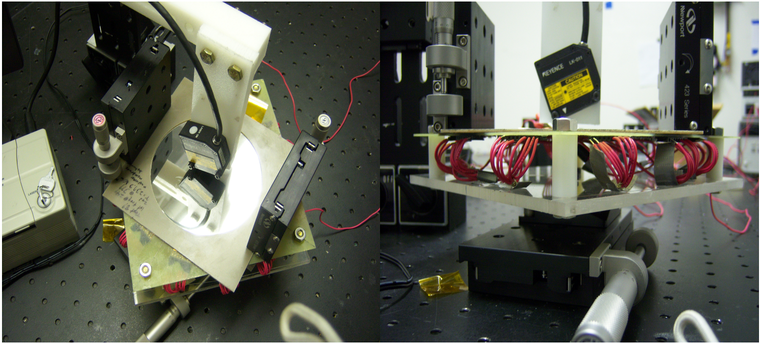
Gap control results



Simulation results; Close trajectory tracking with closed loop control based on dynamic observer estimates; random measurement error and platform vibration

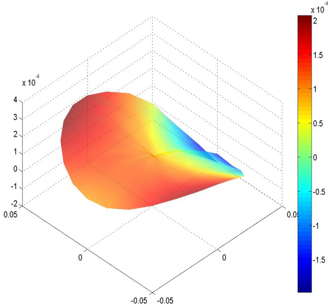
Gap Control: Measurements

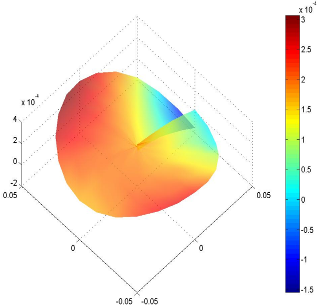
Static measurements



Static tests; surface measurements on the boundary-actuated mirror using a laser displacement sensor.

Gap Control: open loop static measurements





$G_0 = 69\mu$m (Left) and $G_0 = 129\mu$m (Right)

Open loop static tests; all actuators on (at 500 V); focus/defocus mode.

Conclusion

- Two methods examined for electrostatic control of membrane reflectors
- Area Control
  - closed loop control a switching problem
  - precise control seen in simulations
  - oscillations seen in experimental results
- Gap Control
  - continuous control
  - precise control in presence of measurement error and platform vibration
  - concept shown to work in static open loop tests
  - dynamics experiments underway
- Bandwidth, deflection requirements met in both cases

Acknowledgements

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